U.S. DOE 2017 Annual Merit Review and Peer Evaluation Meeting
June 6, 2017

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MAHLE Behr Manufacturing Management, Inc.

UTEMPRA – Unitary Thermal Energy Management for Propulsion Range Augmentation

DOE DE-EE0006840

Project ID:GI157

Driven by performance

Overview

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Timeline

Start Date: October 1, 2014
End Date: February 15, 2018

» Percent Work Complete: 61%

Estimated on March 28, 2017

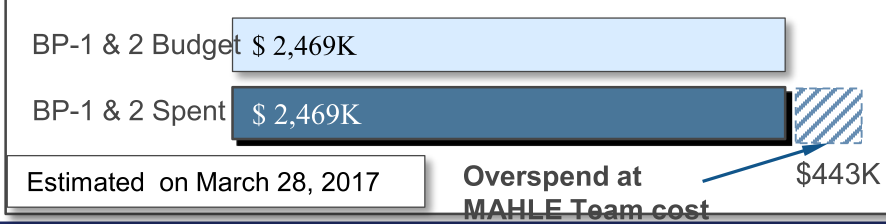
Barriers

- ❑ Severe range penalty occurs for GCEDVs in cold weather (~ 40% range reduction at -10°C) due to resistive heating of cabin
- ❑ Flux contamination of coolant in brazed heat exchangers may lead to corrosion and plugging of small cooling passages in battery and power electronics subsystems
- ❑ Commercial viability associated with numerous coolant valves

Budget

Award No. : DE-EE0006840

Contract Value (80/20):	$ 3,170,379
▪ Gov't Share (with National Lab)	$ 2,536,303
▪ MAHLE'sTeam Share (with National Lab)	$ 634,076



Estimated on March 28, 2017

Partners

FCA
NORGREN
NREL

DELPHI → MAHLE

(Delphi Thermal was acquired by MAHLE on July 1, 2015)

Relevance

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- ❑ Range decrease in winter is a major concern for potential EV customers. OEMs are actively seeking a solution to this issue.
- ❑ UTEMPRA targets to increase range in most heating ambients (-10 to + 20^{0}C)
  - **<u>The quantitative target is to demonstrate range increase</u>** <u>of</u> **<u>15% BEV drive range at -10°C</u>** with equivalent cabin comfort;
- ❑ The team aims to have a commercially viable system with project Technology Readiness Level moved from 3 to 7.

Relative Level of Technology Development	Technology Readiness Level	TRL Definition
System Operations	TRL 9	Actual system operated over the full range of expected conditions.
System Commissioning	TRL 8	Actual system completed and qualified through test and demonstration.
	TRL 7	Full-scale, similar (prototypical) system demonstrated in relevant environment
Technology Demonstration	TRL 6	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment
Technology Development	TRL 5	Laboratory scale, similar system validation in relevant environment
	TRL 4	Component and/or system validation in laboratory environment
Research to Prove Feasibility	TRL 3	Analytical and experimental critical function and/or characteristic proof of concept
Basic Technology Research	TRL 2	Technology concept and/or application formulated
	TRL 1	Basic principles observed and reported

Any proposed future work is subject to change based on funding levels

Project Objectives

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Specific Annual Objectives – Budget Period 2

- **Budget Period 2 (Nov-15 to Mar-17): System Development Phase**
  - » Program management - **Complete**
  - » MMFC Prototype Design and Build **– Prototype 1 (Aluminum) – Complete; Prototype 2 (Plastic) – In Progress**
  - » Braze Equipment Installation and Qualification **- Complete**
  - » Component Builds and Tests (Heat exchangers, Compressor, Valves, Pumps) **– Complete**
  - » System Bench Performance Tests **- Complete**
  - » Complete CoolSim UTEMPRA system Model and use for Vehicle Controls Development **- Complete**

Specific Annual Objectives – Budget Period 3

- **Budget Period 3 (Apr-17 to Feb-18): Vehicle Build and Demonstration Phase**
  - » Program management
  - » Vehicle Controls
  - » Design Durability Validation of Components
  - » Manufacturing Plan and Cost Estimates
  - » Vehicle Build
  - » Vehicle Testing
  - » Final Analysis and Vehicle Delivery

Any proposed future work is subject to change based on funding levels

Resources for BP 3

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No significant resource issues for BP 2

❑ Funds

- Budget Periods 1 & 2 funds were exhausted and MAHLE and Sub-recipients have funded remaining tasks in that timeframe. Current projection indicates project will slightly underspend available DOE/Recipient funding in Budget Period 3 by about 5%. Therefore, the funding is sufficient.

❑ Engineering Human Resources

- MAHLE, Norgren, FCA and NREL - Current team members are available and continuing; Additionally, MAHLE has hired a Controls Engineer and FCA will assign a test engineer.

❑ Equipment and Facilities

- MAHLE's Lockport Climatic Tunnels and Garage will be used for vehicle thermal testing and controls development.
- FCA's vehicle emissions tunnel will be used for range certification
- MAHLE's Flux-free CAB furnace will be used for continuous improvement

Project Timeline

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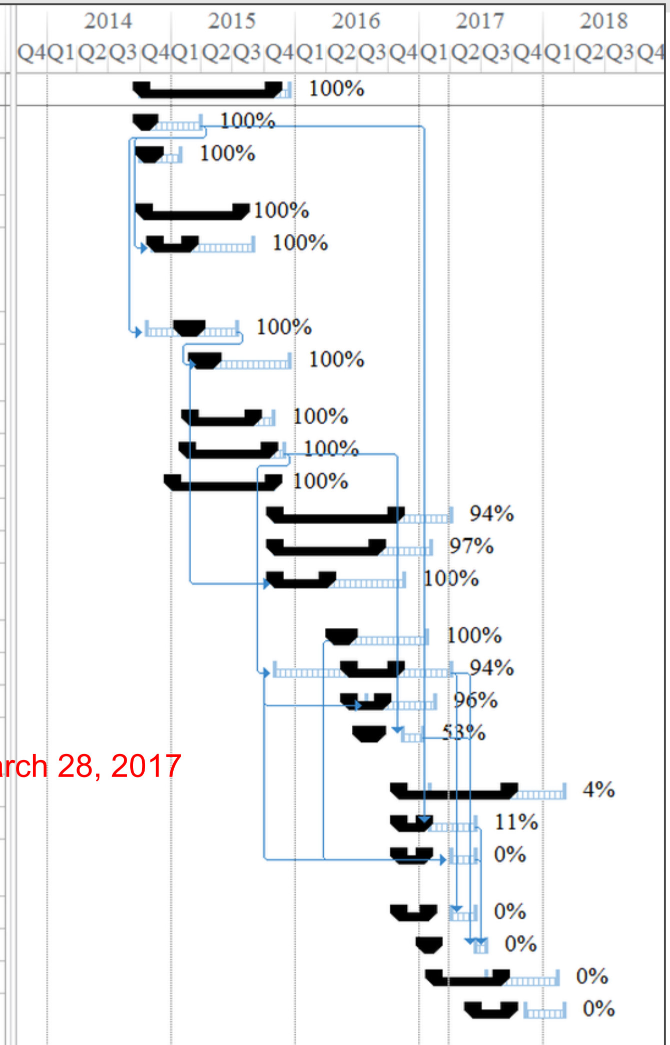
Technology Development

	WBS	Task Name	Baseline Start	Baseline Finish	Actual Start	Actual Finish
1	1	Budget Period 1	10/7/14	10/28/15	10/1/14	12/15/15
2	1.1	Vehicle Requirements	10/7/14	10/29/14	10/23/14	3/31/15
8	1.2	Refrigerant, Lubricating Oil, Coolant & Compressor Selection	10/14/14	11/13/14	10/1/14	1/29/15
14	1.3	Vehicle CAD Data	10/14/14	7/27/15	10/15/14	7/7/15
20	1.4	Vehicle Baseline Tests (HVAC Performance, Energy Usage, Range Effect)	11/13/14	2/24/15	11/7/14	8/31/15
29	1.5	System & Component Specifications	2/2/15	3/17/15	10/22/14	7/15/15
45	1.6	Heat Exchanger Design, Analysis & Optimization	3/17/15	5/6/15	4/1/15	12/15/15
61	1.7	Unitary System Vehicle Modeling	2/24/15	9/2/15	2/26/15	10/31/15
71	1.8	Flow Control (Coolant)	2/17/15	10/16/15	2/19/15	11/30/15
109	1.9	Brazing Equipment Spec and Order	1/5/15	10/28/15	1/7/15	10/30/15
115	2	Budget Period 2	11/2/15	10/26/16	11/2/15	NA
116	2.1	Prototype Design / Build	11/2/15	8/30/16	11/2/15	NA
145	2.2	Brazing Equipment Qualification, Tooling & Component Build	11/2/15	4/7/16	11/2/15	11/17/16
174	2.3	Component & System Tests	4/26/16	6/9/16	4/26/16	1/25/17
193	2.4	System Bench Performance Tests	6/9/16	10/26/16	11/2/15	NA
211	2.5	Vehicle Controls Study	6/9/16	9/15/16	8/1/16	NA
217	2.6	Human Machine Interface or Information Display	7/14/16	9/1/16	11/14/16	NA
221	3	Budget Period 3	11/1/16	9/22/17	2/1/17	NA
222	3.1	Vehicle Controls	11/1/16	1/17/17	2/1/17	NA
238	3.2	Design Durability Validation - Components	11/1/16	1/16/17	NA	NA
247	3.3	Manufacturing Plan & Cost Estimates	11/1/16	1/26/17	NA	NA
272	3.4	Vehicle Build	1/18/17	2/14/17	NA	NA
279	3.5	Vehicle Testing	2/15/17	8/31/17	NA	NA
314	3.6	Final Technical Analysis & Vehicle Delivery	6/7/17	9/22/17	NA	NA

System Development

Vehicle Demonstration



Any proposed future work is subject to change based on funding levels

Milestones

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Target Date	Milestone	Status
Nov-14	Milestone 1: Rough Vehicle Packaging Study	Complete (Dec-14)
Feb-15	Milestone 2: System Specification	Complete (Mar-15)
Apr-15	Milestone 3: Component Design	Complete (Jun-15)
Jul-15	Milestone 4: Proof-of-Concept (POC) Manifold and Valve Design	Complete (Aug-15)
Oct-15	Milestone 5: and **Go-No-Go 1:** POC Manifold and Valve Build	Complete (Oct-15)
Jan-16	Milestone 6: Braze Equipment Installed and Qualified	Complete (Apr-16)
May-16	Milestone 7: Heat Exchanger and Compressor Build	Complete (Dec-16)
Sep-16	Milestone 8: Bench Test Complete	Complete (Mar-17)
Oct-16	Go-No-Go 2: Bench Test Comple	Meeting Complete (Mar-17); Passage pending

Project Approach – Baseline BEV

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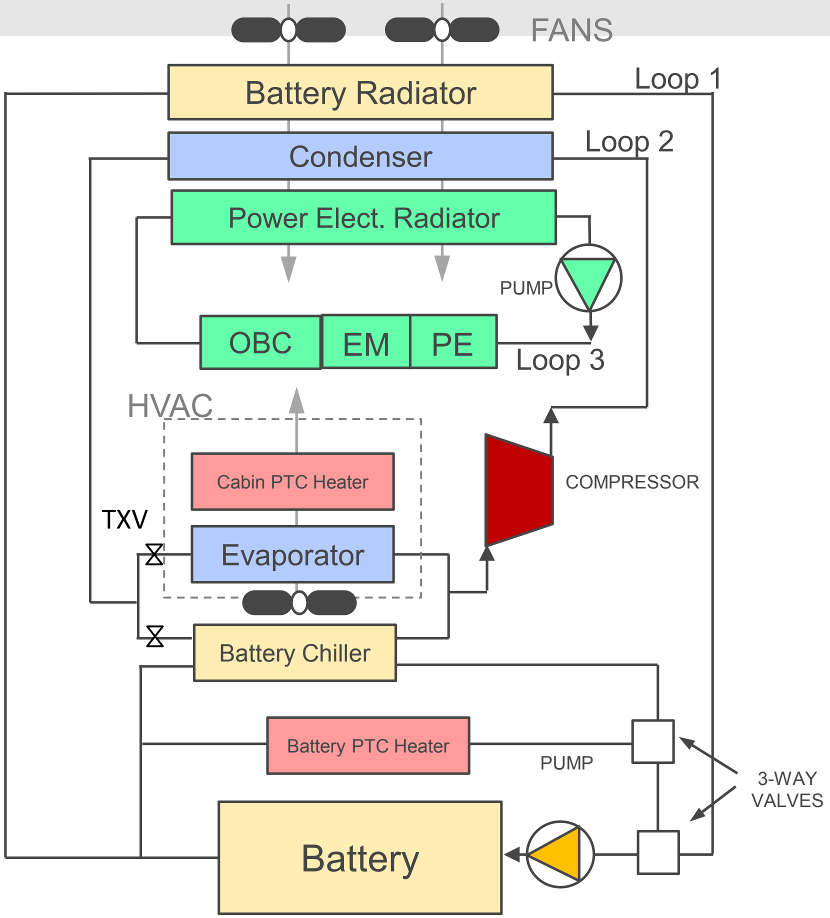
Image courtesy of FCA

2015MY Fiat 500e BEV

- Cooling: Traditional Direct A/C System
  Heating: PTC Heater (qty. 2)
- Thermal Conditioning of Battery, Power Electronics and Cabin are independent
- Two PTC (Resistive) Heaters for the Cabin and Battery - significant drain on the battery
- Relatively simple control but no heat recovery/thermal optimization applied



2015 Fiat 500e Thermal Management System

OBC – On-board Charger
EM – Electric Motor (Vehicle Propulsion)
PE – Power Electronics (Inverter)

Project Approach – UTEMPRA

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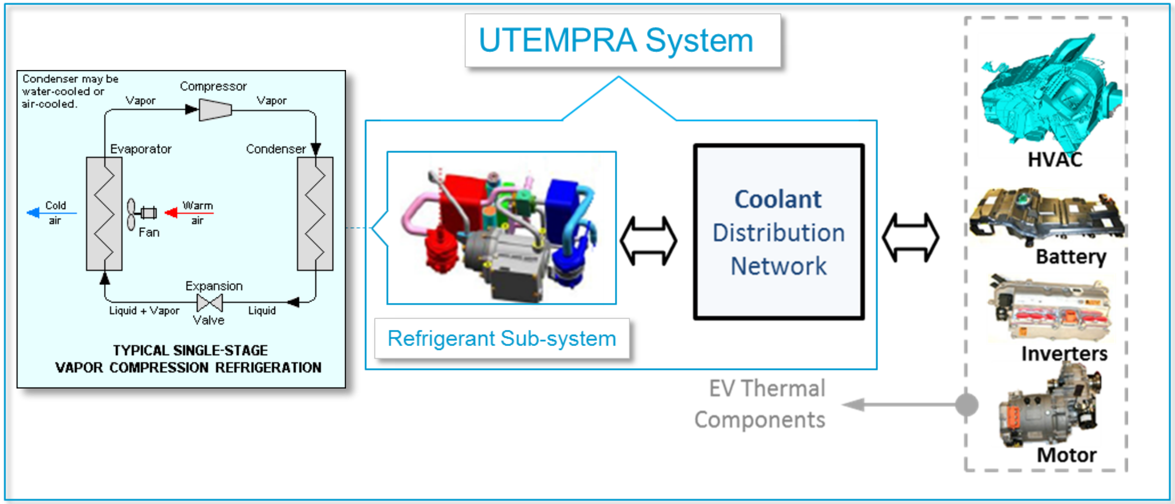

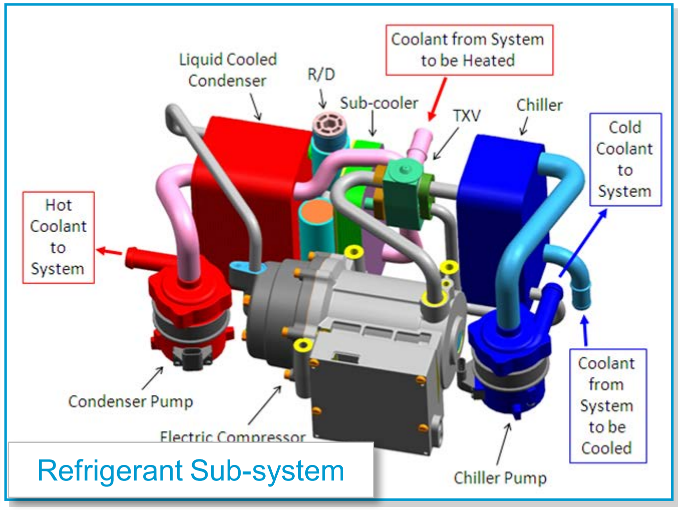

UTEMPRA Benefits

- ❑ Compact refrigerant sub-system generates heating and cooling – continuously available and deployable
- ❑ Coolant architecture enables heat scavenging – improved fuel economy
- ❑ Coolant-based heat pump system is more simple and more flexible vs. refrigerant-based heat pump systems
- ❑ Significant refrigerant savings (est. 50% vs. ref. based heat pump systems) – cost and environmental benefit

Project Approach – Schematic

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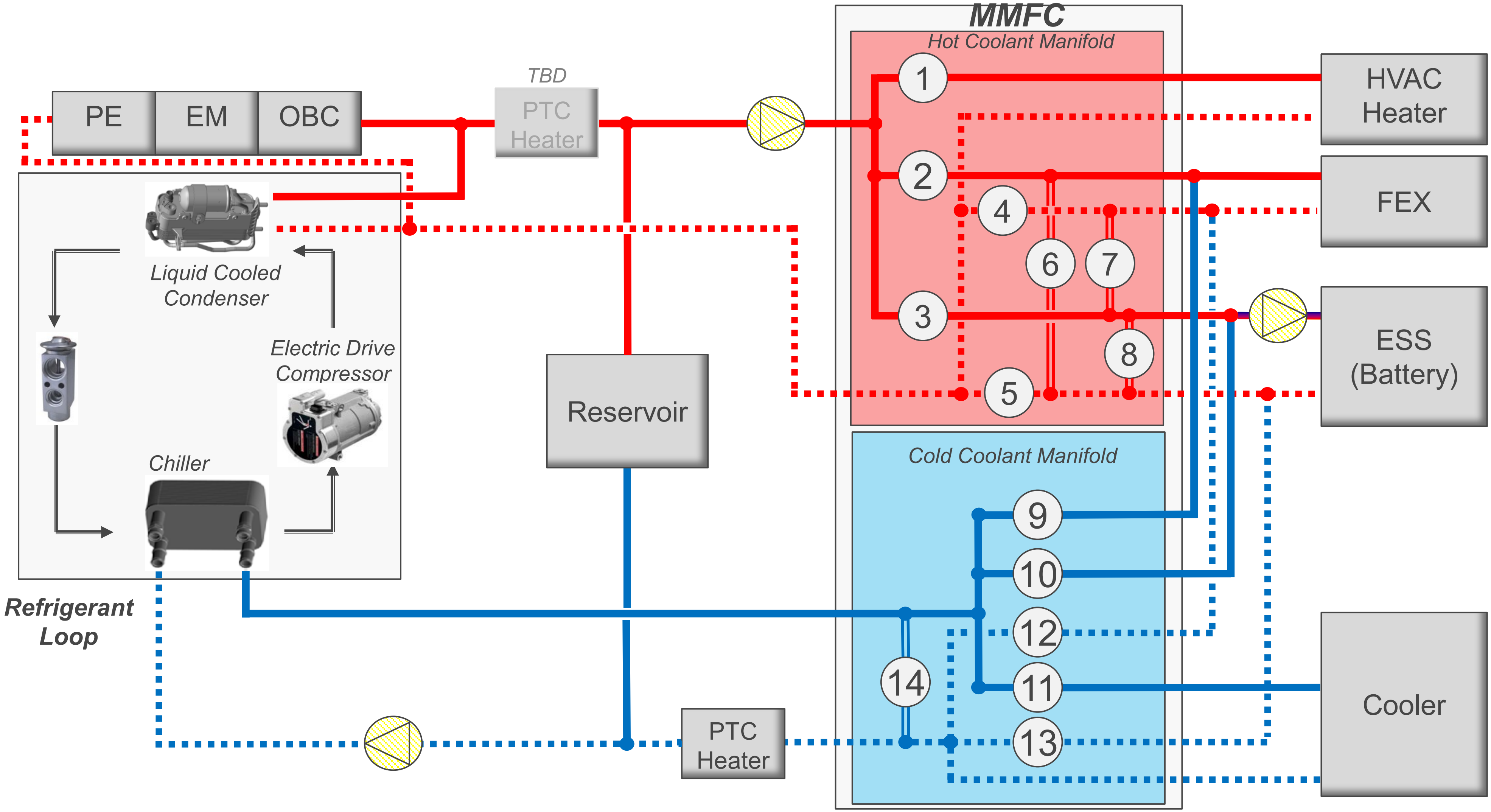

Project Approach – UTEMPRA

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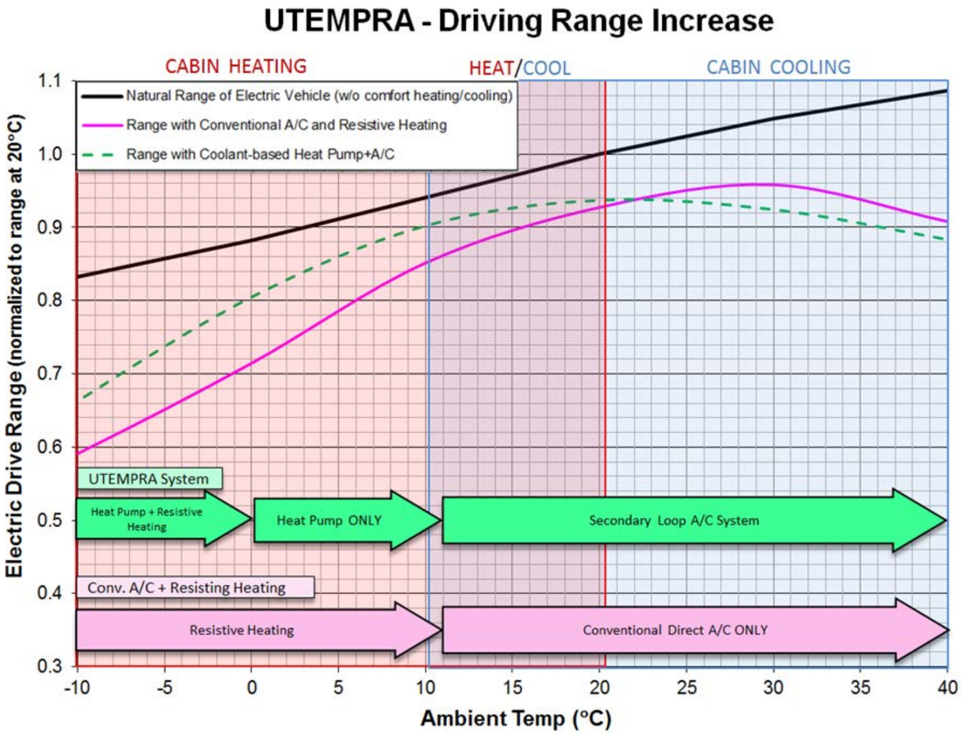
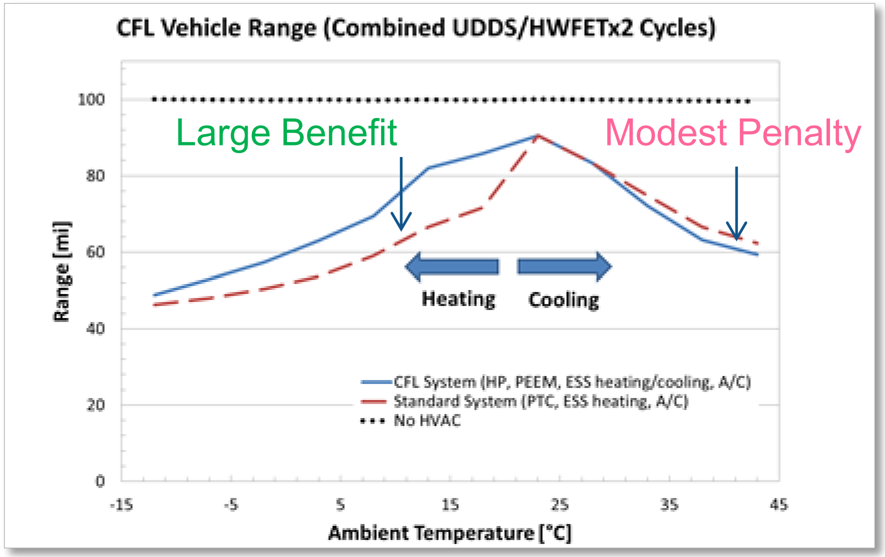


NREL Bench Test + Simulation Study

- 9% Range improvement annual weighted
- ~12% improvement at -10°C (components and system not optimized)



D. Leighton et al. SAE 2014

- Internal studies and NREL study has shown 15% range improvement target is quite feasible
- A Coolant-based thermal loop system that is commercially viable will enable use of other energy saving technologies such as PCM storage, idle-stop savings etc.

Technical Accomplishments –
1st Generation MMFC

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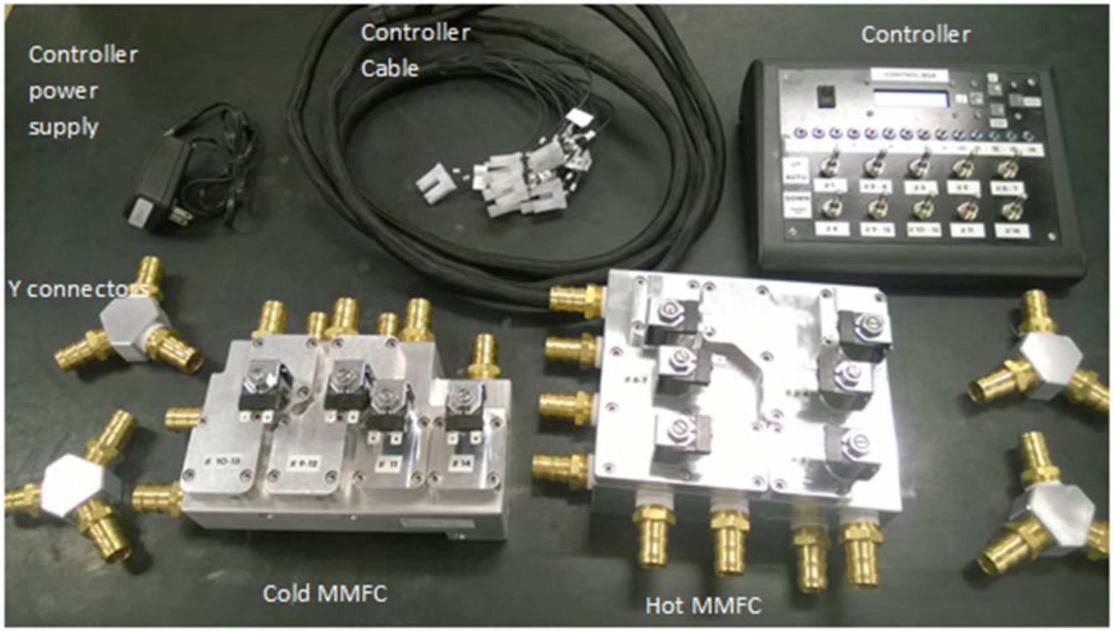

MMFC proof-of-concept parts

MMFC installed in coolant network simulator

- Extensive tests revealed leakage observations with 1st Generation MMFC in some modes due to lack of/ reversal of pressure difference.
- Leakage from hot to cold loop and vice versa will negatively impact performance of system.

Technical Accomplishments -
Effect of Internal Coolant Leakage

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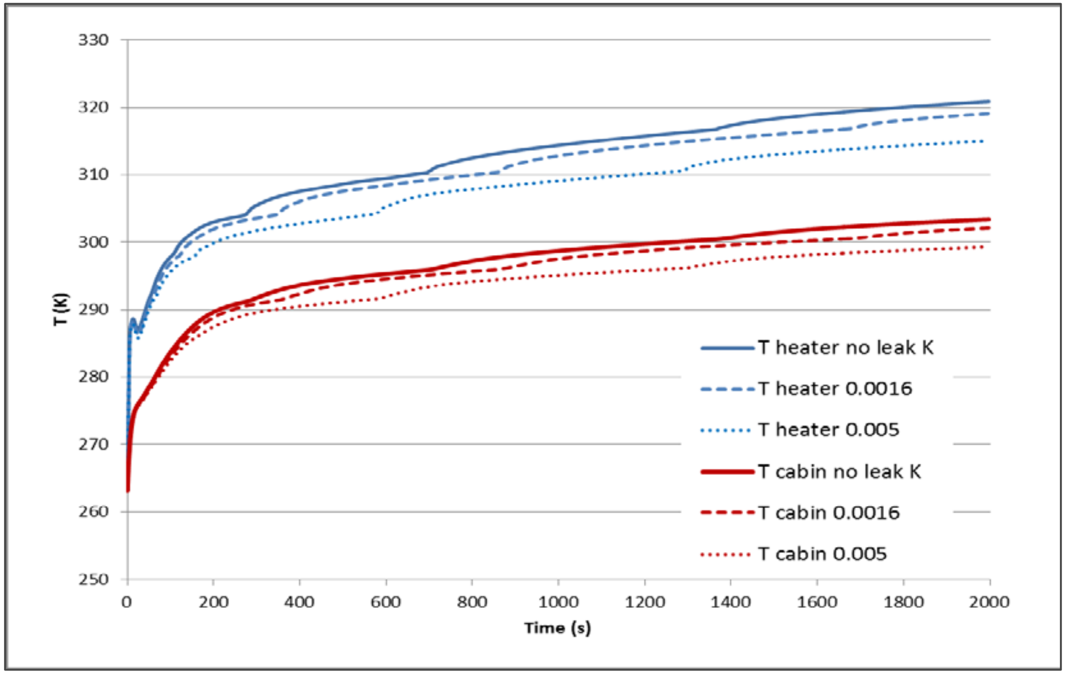

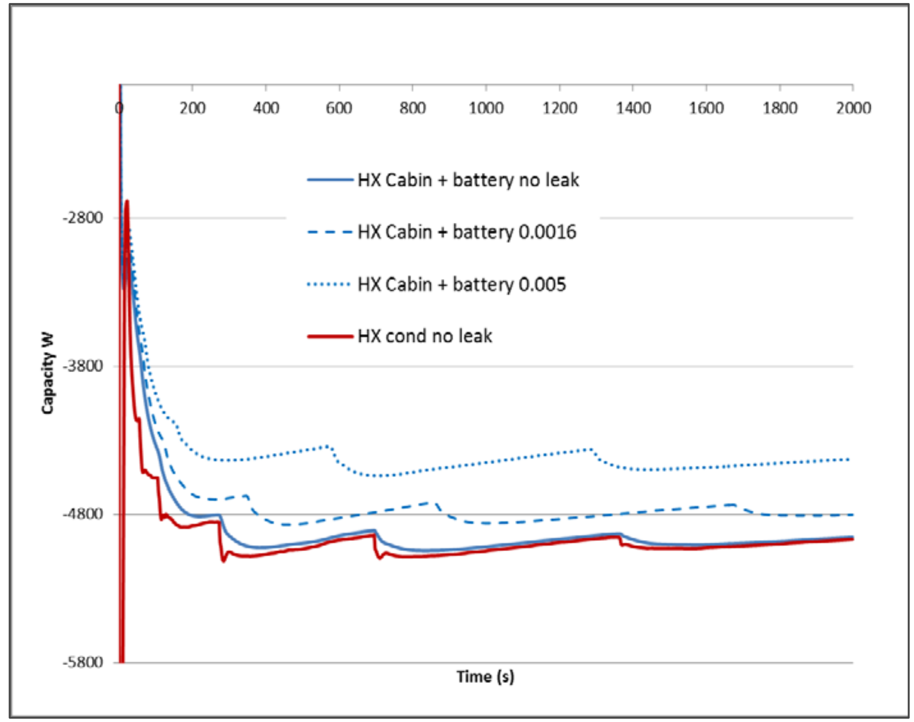

Leak rates of 0.0, 0.1 and 0.3 LPM considered above

- Simulation of effect of leakage rates on Heater Air Discharge temperature and Cabin temperature
- MAHLE's previous experience shows leakage >0.1 LPM will be significant enough to deteriorate the system benefits.

Technical Accomplishments –

2nd Generation MMFC

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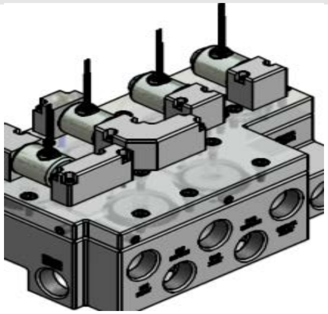

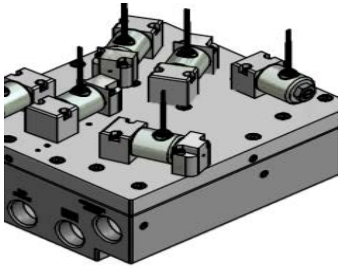

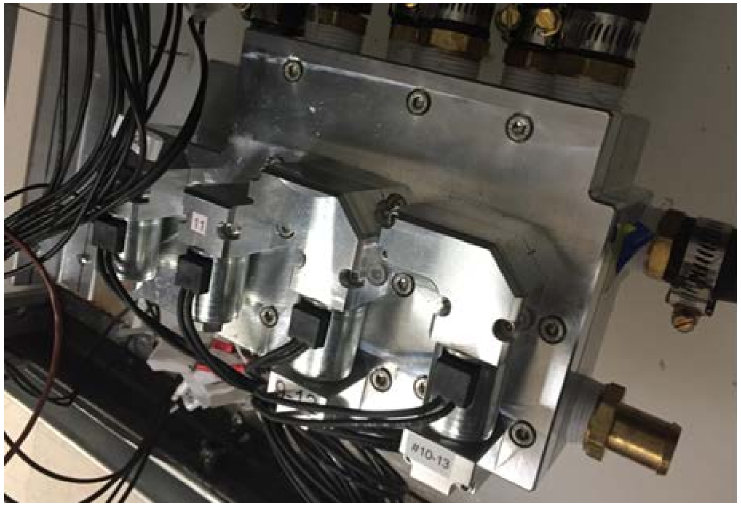

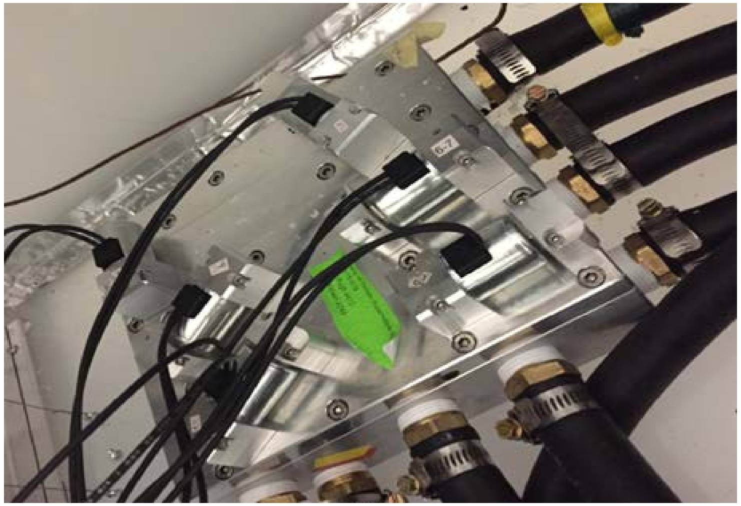

- ❑ Leakage issue is fully addressed with design change to 2nd Generation MMFC. Tests have confirmed it at component level & bench level
- ❑ First version of this 2nd Generation MMFC was produced using Aluminum body to expedite component build for NREL Bench. The second version will be made of plastic (production-intent)

Technical Accomplishments –
Flux-free Brazing Furnace Specification

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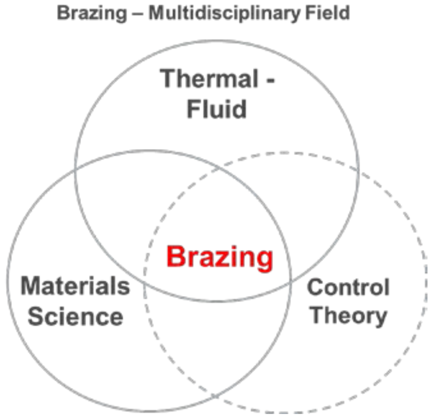
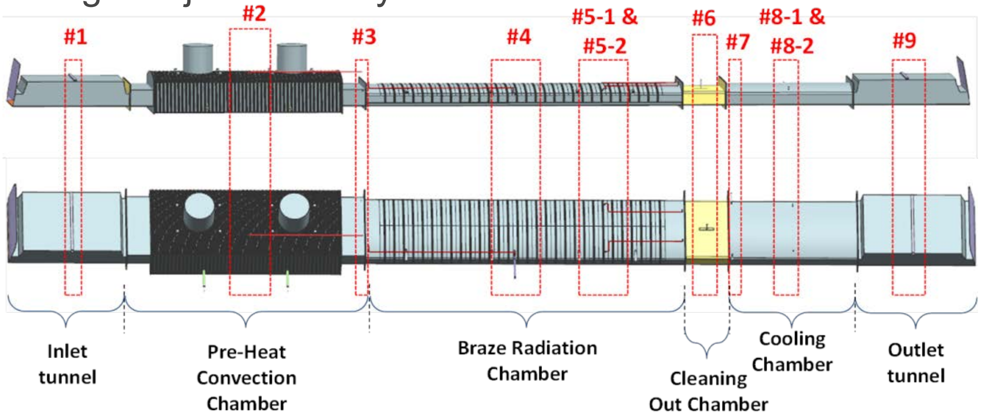
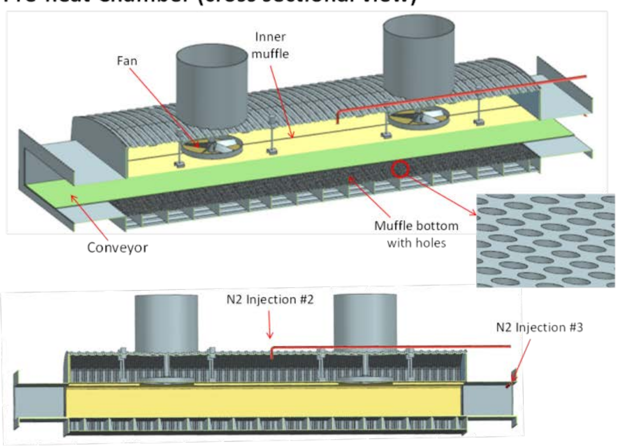
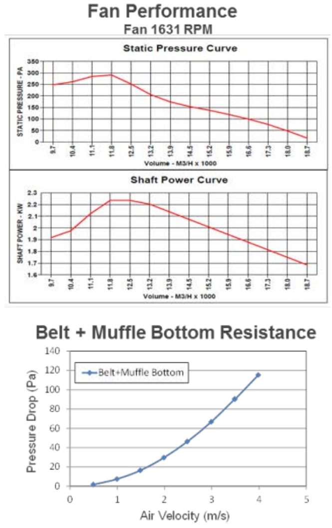


Nitrogen Injection Analysis



Pre-heat Chamber (cross sectional view)





- ❑ Braze Furnace specification was made after detailed CFD study of nitrogen injection and heat transfer.
- ❑ Lockport furnace has shown excellent control on braze parameters:
  - Dew point below -85°C
  - O_2 level below 15 ppm

Technical Accomplishments –
Flux-free Development Timeline

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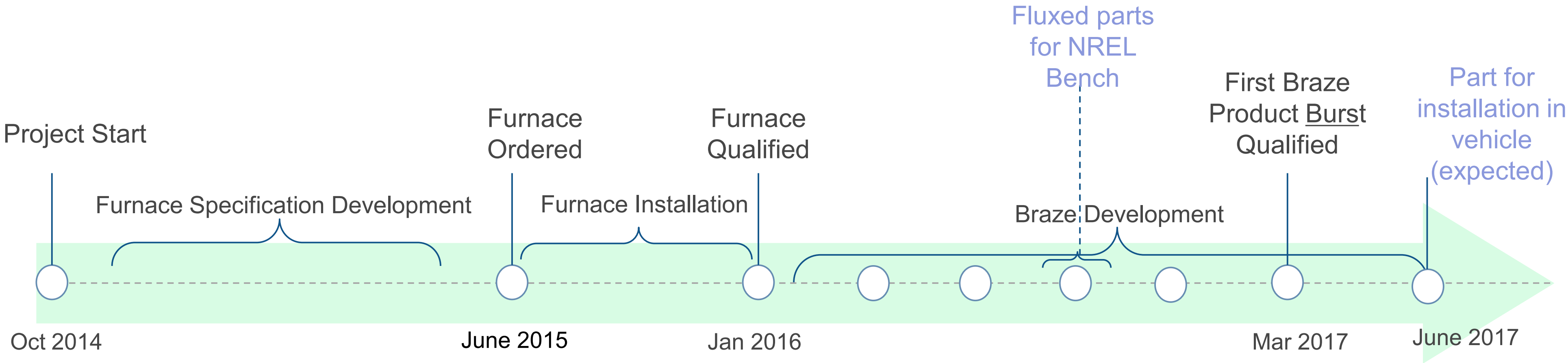

Five heat exchangers classified by two construction types:

A. Plate-type constructions (alternating plate and fin)
- Chiller
- Liquid Condenser

B. Tube-type constructions (headered tubes and louvered fins)
- Heater
- Cooler
- FEX

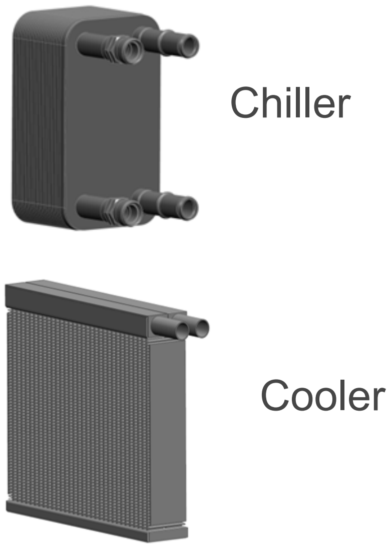

Plate-type construction is significantly more challenging; also it has most flux residue

Any proposed future work is subject to change based on funding levels

Technical Accomplishments –
First Flux-Free Plate-type Chillers

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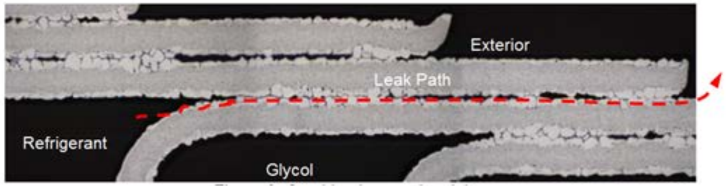
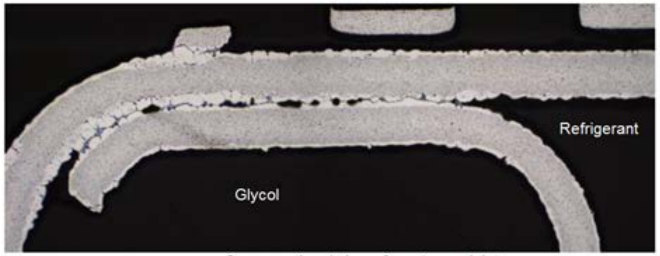
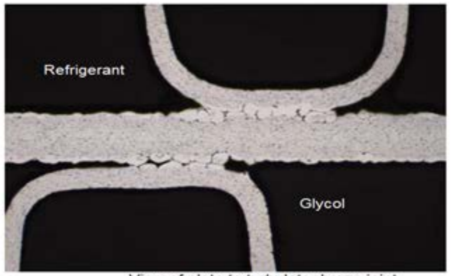


Outside plate-to-plate



Cross sectional view of cup to cup joint.



View of plate to turbulator braze joint.

Turbulator = interior fin

Technical Accomplishments –
Qualified Inner Braze – Cup-cup & Fin-Plate (March 2017)

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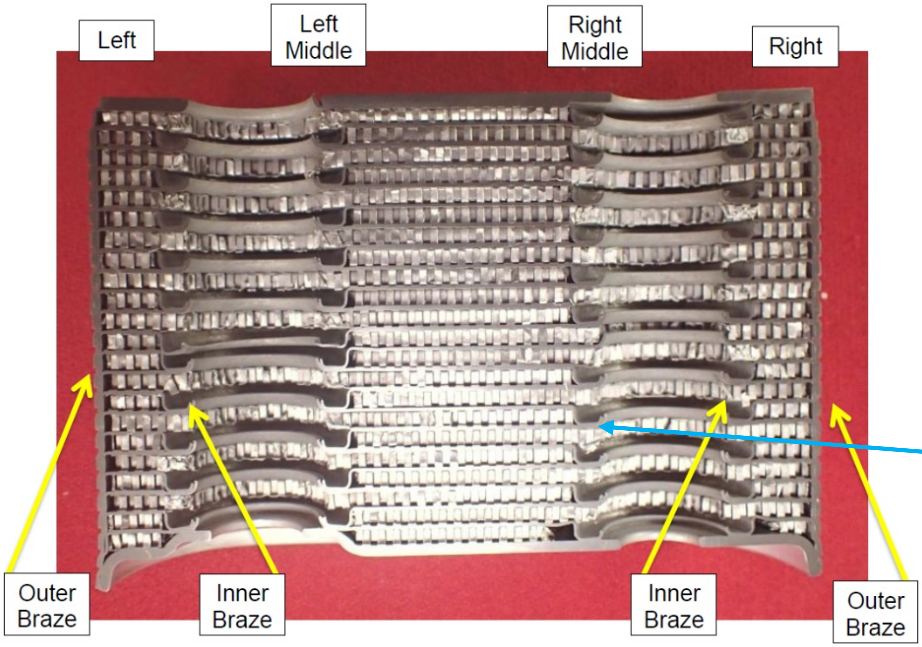

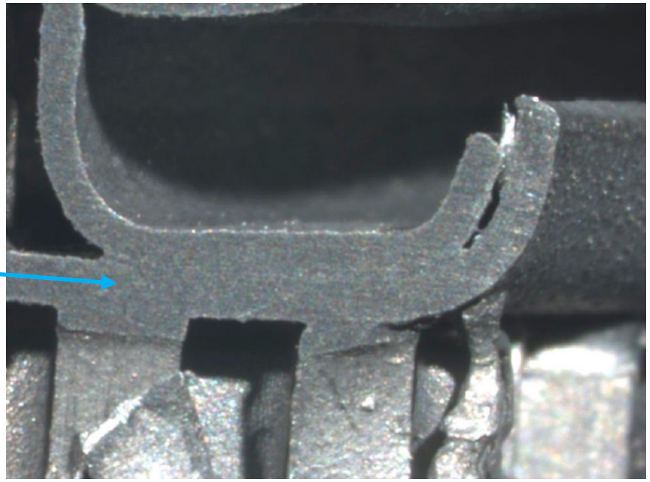

- ❑ Significantly improved bonds without porosity
- ❑ Further improvement is expected with a new 2nd generation flux-free material

Technical Accomplishments –
Flux-free Parts have passed Burst Requirement

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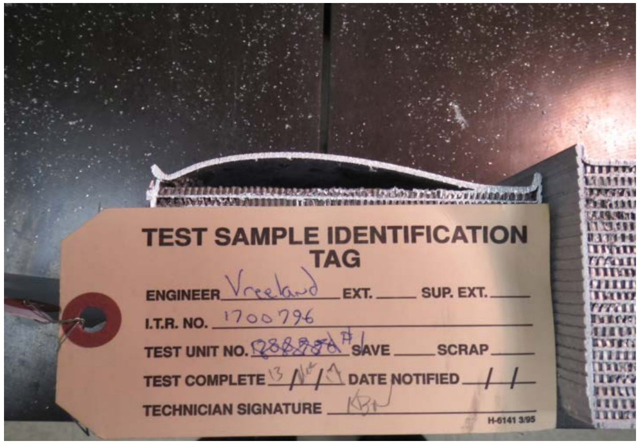

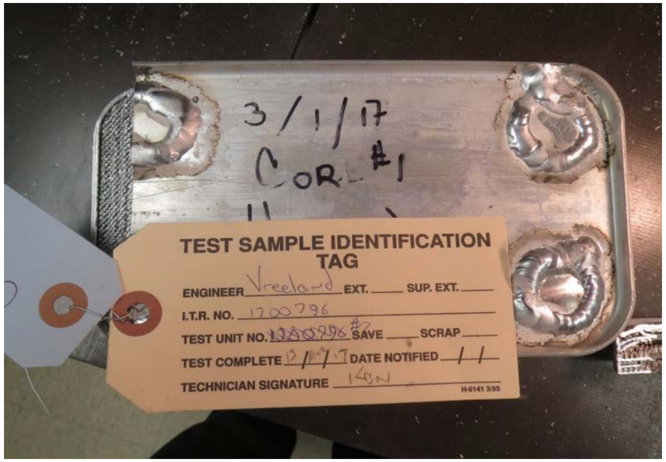

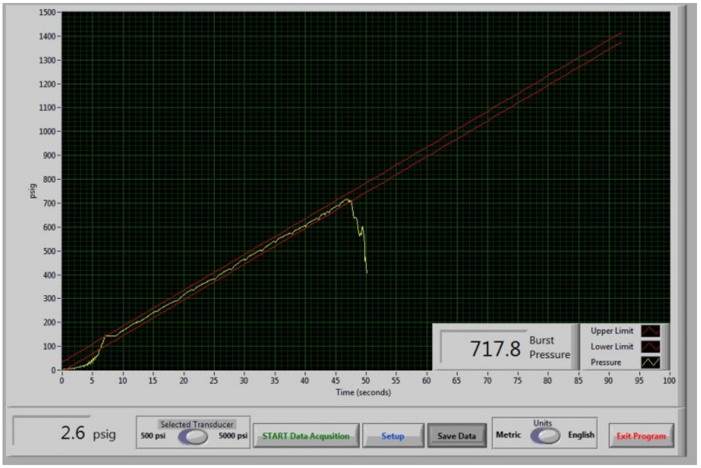

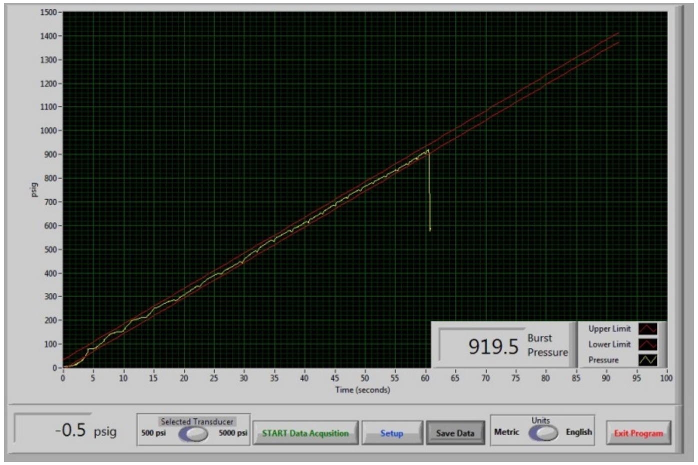

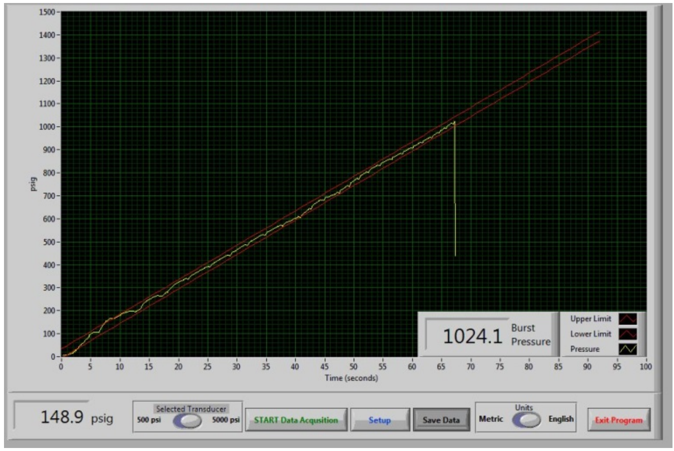

Three flux-free parts have exceeded the burst requirement of 450 psig

Technical Accomplishments –
Components Design and Build

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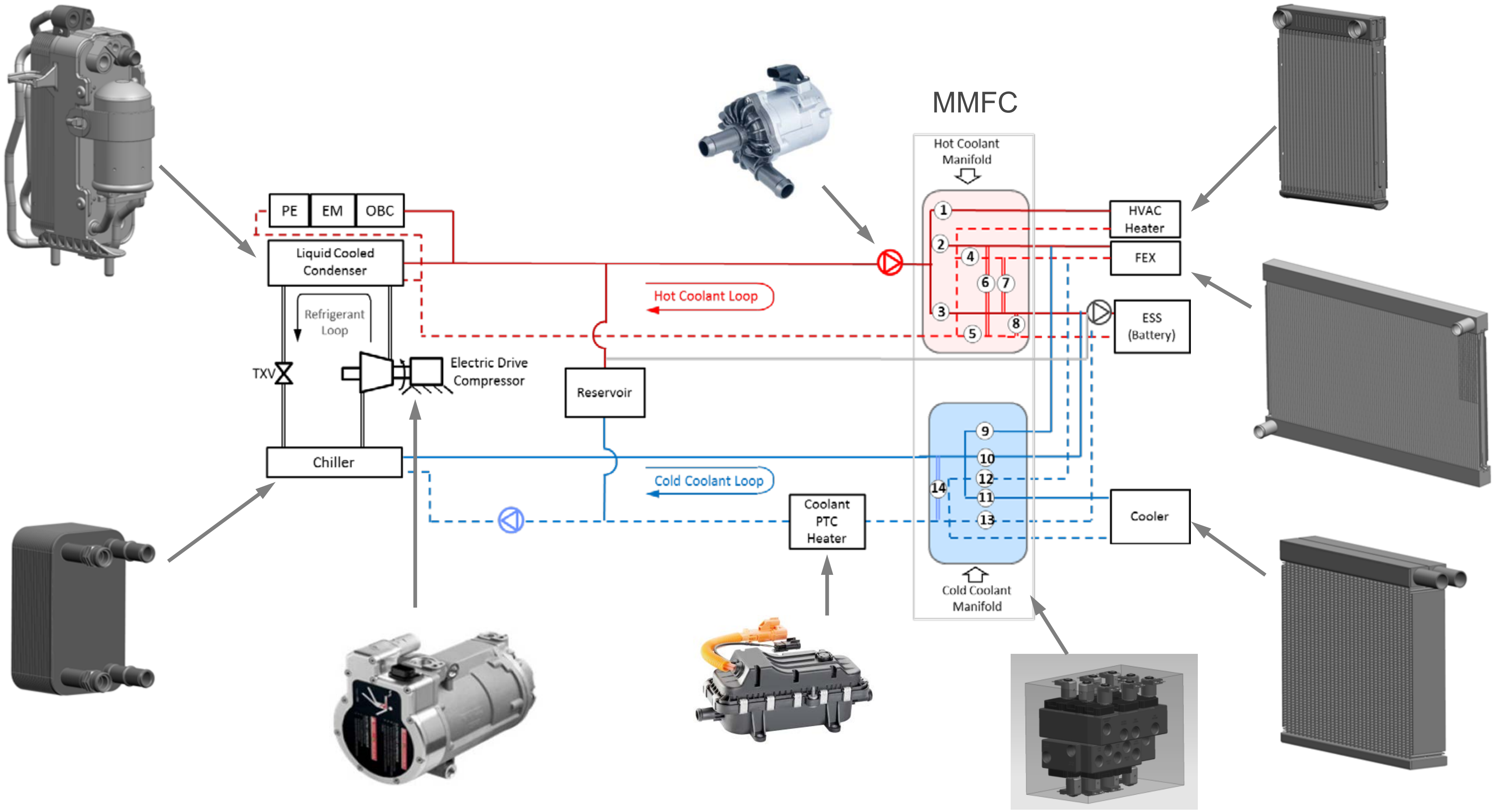

Technical Accomplishments –
Components Design and Build … continued

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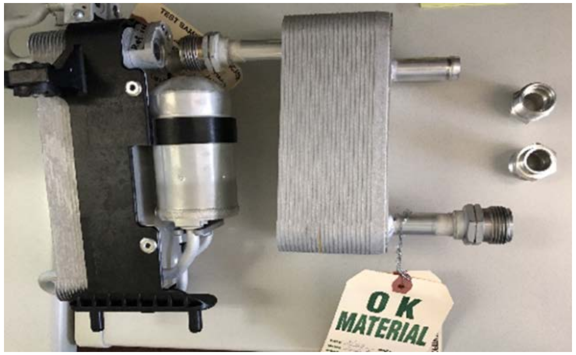
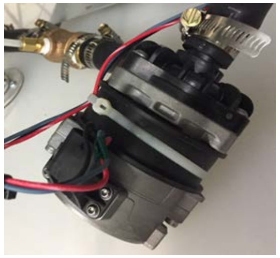


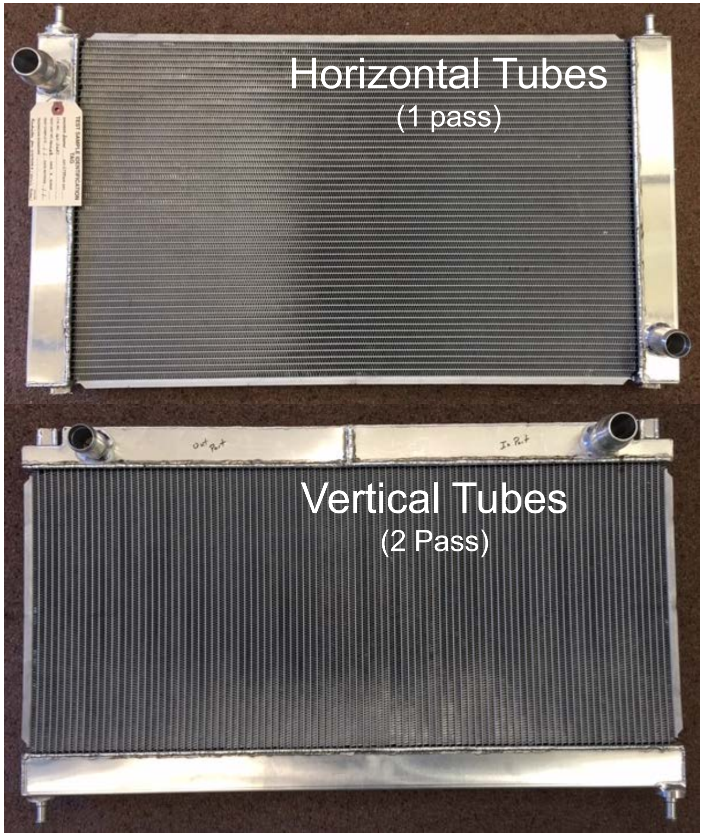
LCC and Chiller

ED36cc Compressor

Heater and Cooler



Coolant Pump



FEX

Technical Accomplishments –
UTEMPRA Bench Build at NREL, Golden, CO

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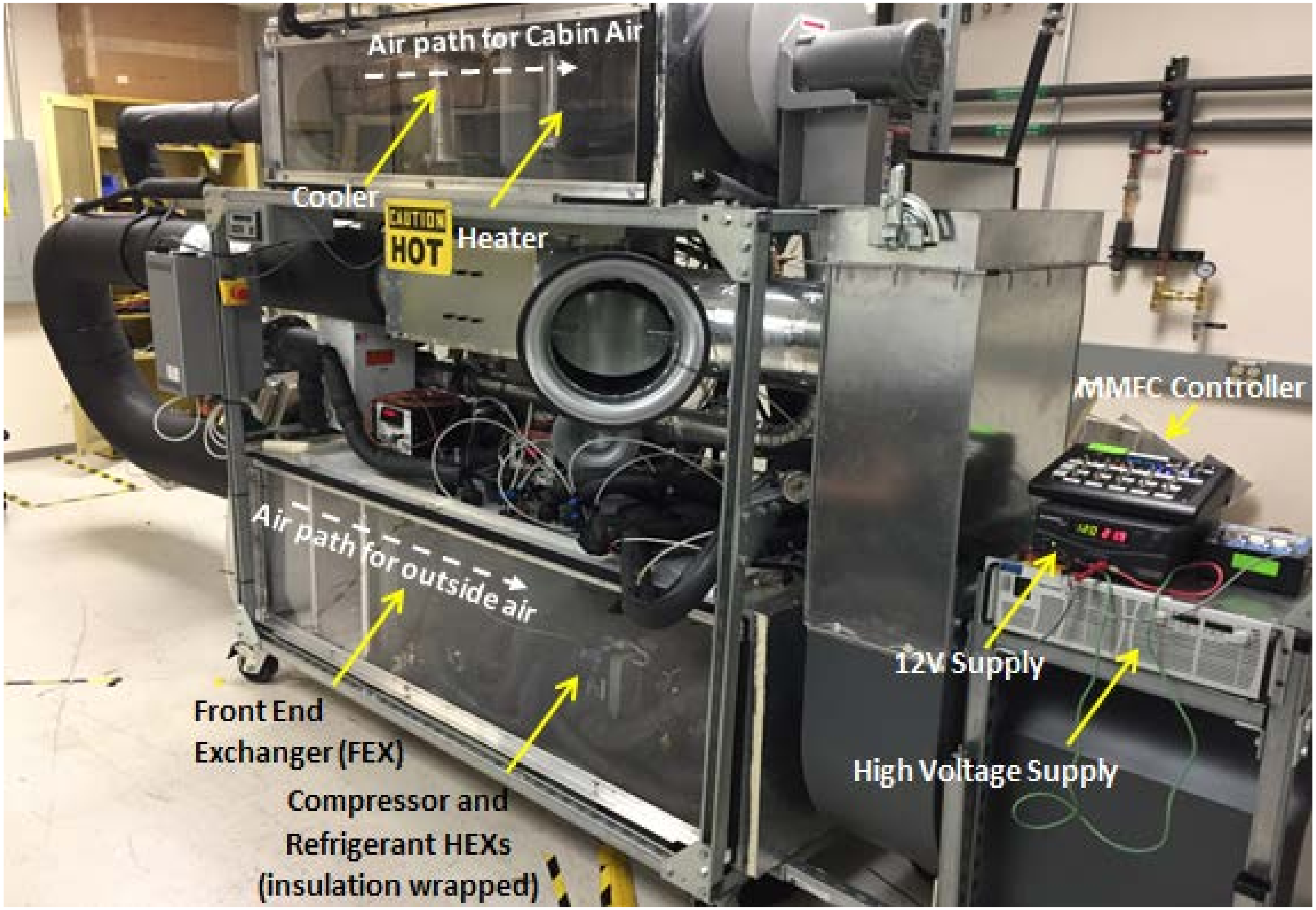

Technical Accomplishments –
NREL Testing

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Mode Sweep Test

- ❑ verify successful mode valve opening/closing
- ❑ verify absence of leakage

Cooling Mode Test

- ❑ 43.3 C x 19% r.h.
- ❑ 35 C x 40% r.h.

Heating Mode Test

- ❑ 2.5 C
- ❑ 0 C
- ❑ -6.5 C

Technical Accomplishments –
Projected Data - Ambient *minus* 10 C

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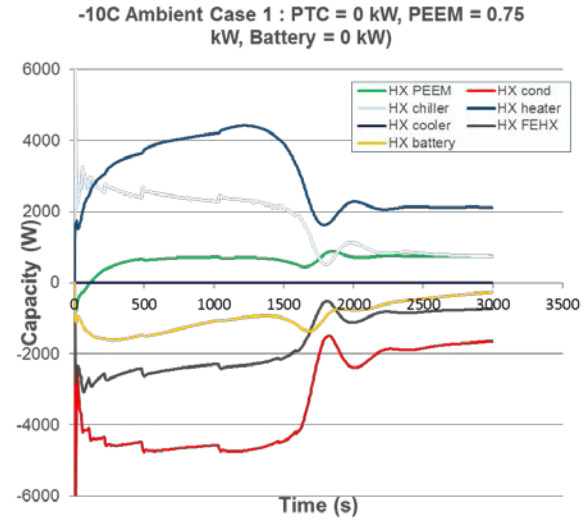

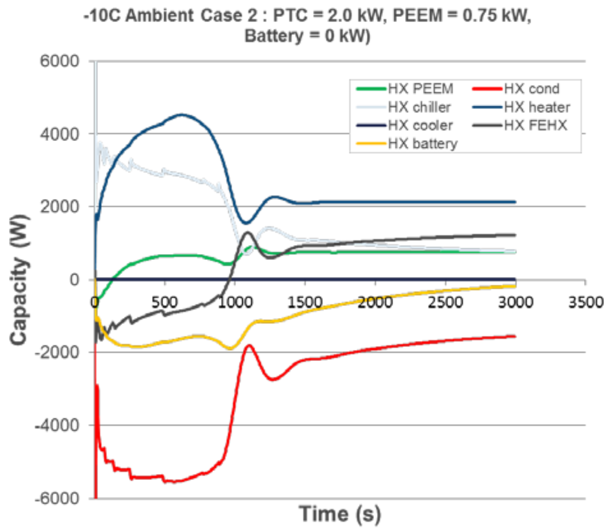

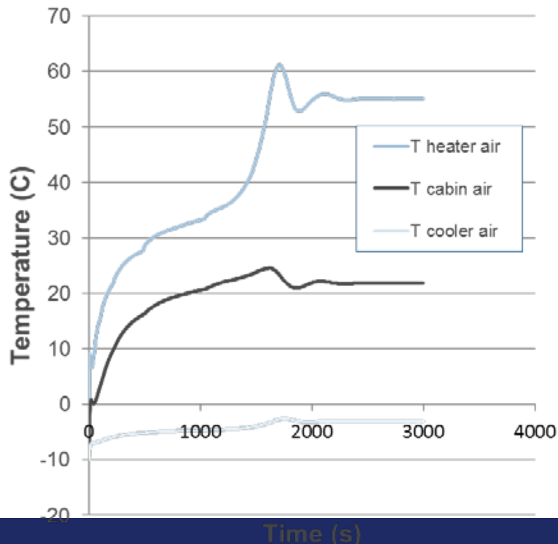

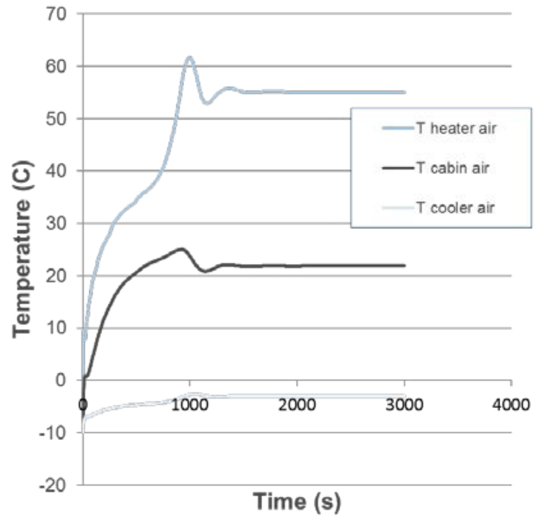

Technical Accomplishments –

Range Impact Estimate - Ambient at -10^{o}C

Mode 20 ESS-NTM and Cabin Heating, 40 km/h

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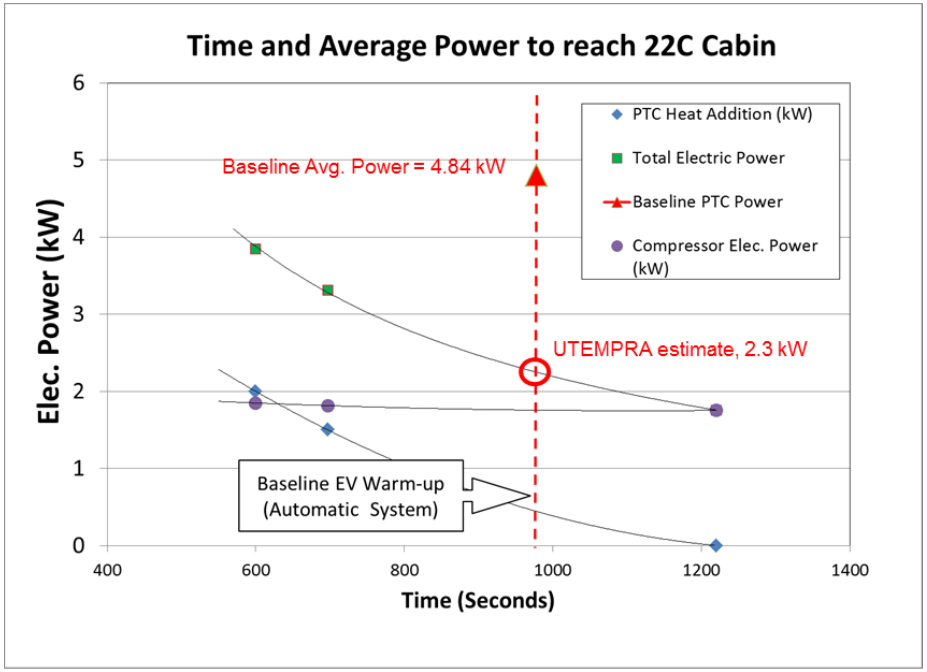
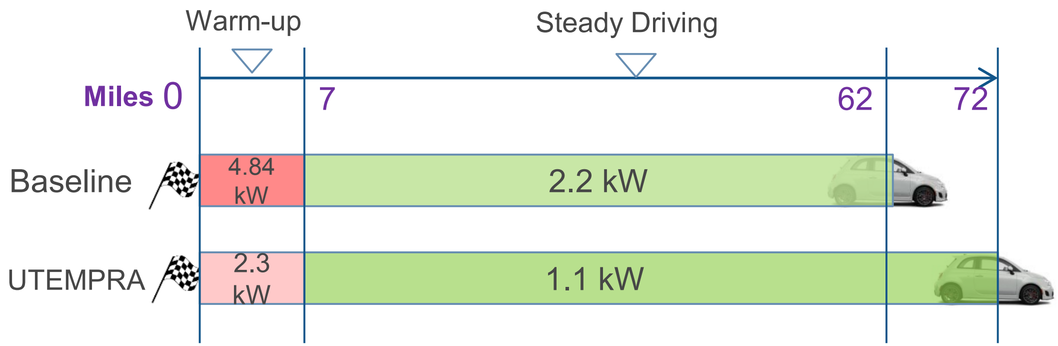


Climate Control Electric Power at -10^{o}C



- ❑ Estimated Electric Power Savings:
  - Cabin Warm-up Period, 16 mins @ 2.5 kW is 2.5x16/60 = 0.67 kWh
  - Steady State Period, 133 mins @1.1 kW is 1.1 x 133/60 = 2.44 kWh
- ❑ Baseline vehicle has 3.08 miles/kWh; this produces extra 9.6 mile
- ❑ Baseline vehicle range at -10C is 62 miles; therefore, estimated increase is 15.5%

Response to Previous Years Comments
Slide 1 of 2

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- ❑ Majority of comments are neutral/favorable; comments with some concerns are addressed here

Question 1: Approach to performing work

- … "Performance targets and verification must include operation below -10℃ ambient."

RESPONSE: UTEMPRA retains one of two baseline PTC heaters for rapid warm up supplementary heating and for operation below -10ºC ambient. Heat pump heating will be available down to -10 or -12ºC ambient, but most US ambients are above that. FMVSS tests and heating at ambients below -10ºC will be tested.

- … "whether the choice of this OEM and vehicle type would in any way limit the potential broader commercial applicability"

RESPONSE: Vehicle type will not affect the design of the system. Some variations to the UTEMPRA architecture may occur depending on vehicle and OEM needs, but in principle, coolant-based heat delivery through a manifolded valve system remains attractive.

- .. "The reviewer asserted that the driving range extension should be looked into over the whole year"

RESPONSE: Indeed, the team is considering range extension across the whole year. Gains on heating side off-sets modest range decrease in the cooling side. The goal is to have a relatively flatter range vs ambient curve across.

Question 2: Technical Accomplishments

- … "no details as to the potential cost premium although the target is apparently to achieve cost neutrality with today's conventional HVAC systems"

RESPONSE: Details of cost figures are proprietary information. UTEMPRA has additional parts but replaces baseline vehicle's three front-end exchangers with a single exchanger and two PTC heaters with a single heater. Innovation of valve system unification brings cost close to parity. In balance, range increase is significant.

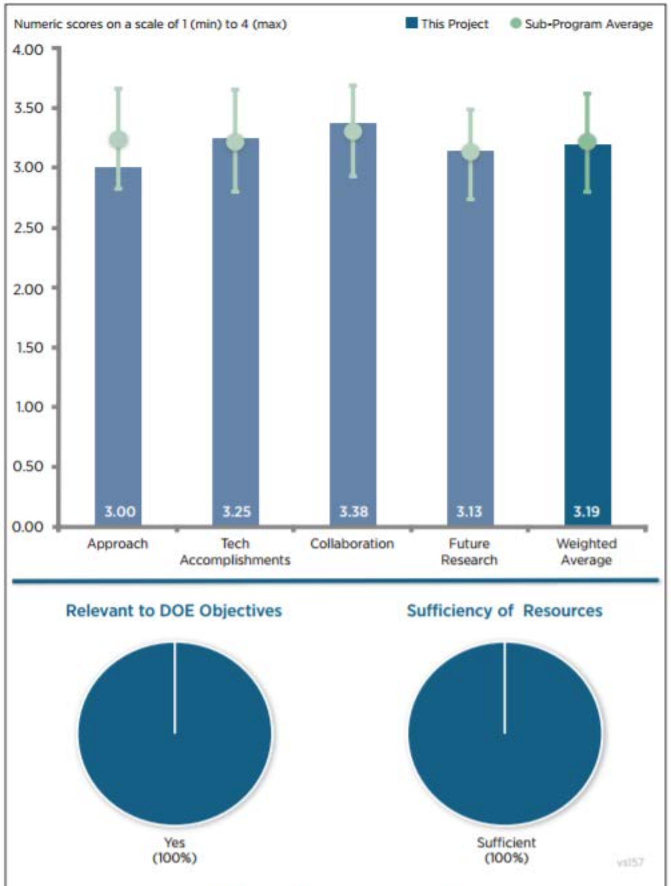

Figure 1-23 – UTEMPRA - Unitary Thermal Energy Management for Propulsion Range Augmentation: Sourav Chowdhury (Mahle Behr USA LLC) - Vehicle Systems

2016 UTEMPRA scores

Any proposed future work is subject to change based on funding levels

Response to Previous Years Comments
Slide 2 of 2

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Question 3: Collaboration and Coordination

- … "Getting more OEMs involved might help."

RESPONSE: UTEMPRA type system is attractive to several OEMs and we are separately engaged with multiple OEMs who seek coolant-based architecture. However, due to NDAs and terms of project, we cannot directly share information with other OEMs.

Question 5: Proposed Future Research

- … "The reviewer wanted to see future work include a cost and performance comparison with increased battery size"

RESPONSE:MAHLE Team thinks that this technology (primarily, heat pump) will remain relevant irrespective of battery size as range loss in cold climate due to resistive heating will remain a cause for customer anxiety in adopting EVs over conventional ICE vehicles. Customers prefer a flatter range vs ambient curve, just like in ICE vehicles. UTEMPRA system will contribute to making EV performance less dependent on weather. However, UTEMPRA will be one of the several innovations in that respect.

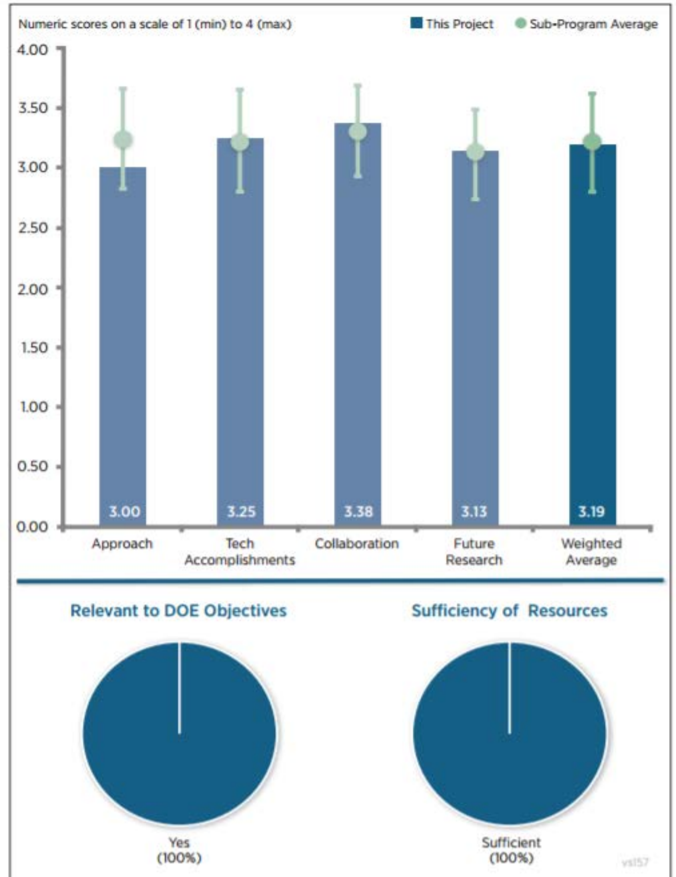

Figure 1-23 – UTEMPRA - Unitary Thermal Energy Management for Propulsion Range Augmentation: Sourav Chowdhury (Mahle Behr USA LLC) - Vehicle Systems

2016 UTEMPRA scores

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Summary of Technical Accomplishments in BP2

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- Proof of concept design of MMFC has been modified. Two levels of prototype MMFC – Aluminum (complete) and Plastic (to be made). Aluminum version is tested successfully on bench (**Norgren**, **MAHLE**)
- Flux-less braze furnace was installed and qualified with successful trial runs (**MAHLE**)
- After several iterations of flux-free runs, first chiller parts qualified with burst pressure tests. MAHLE looks forward to put a flux-less part on the vehicle (**MAHLE**)
- System components have been fabricated and tested. (**MAHLE**)
- UTEMPRA System bench has been assembled and tested in both heating and cooling modes (**NREL,** **MAHLE**)
- Early projections using calibrated simulation model and test data show 15% range improvement at -10C viable. (**Norgren**, **MAHLE**)
- UTEMPRA Controls study planned for BP 2 is complete with many information exchanges. (**MAHLE**, **FCA**)

Any proposed future work is subject to change based on funding levels

Collaboration & Coordination with Partners

MAHLE

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Excellent collaboration achieved in BP 2

- Bi-weekly Meetings (Webex) among all partners
- Multiple site visits from Main Recipient to Sub-recipients
  - FCA, Auburn Hills, MI
  - NREL in Golden, CO
  - Norgren, Farmington, CT
- Joint patent application planned (MAHLE-Norgren)
- MAHLE saved significant time and money for Norgren by machining the manifold prototype 1 part for Norgren

Remaining Challenges and Barriers

MAHLE

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- Challenge 1: Design and validate a Multimode Fluid Controller (MMFC)
  - Prototype 1 in aluminum of 2nd Generation MMFC is functionally validated, validation of Prototype 2 in plastic in vehicle remains a low to medium risk
- Challenge 2: Develop a braze recipe for flux-free braze materials
  - Recent success with flux-free parts has reduced this risk significantly. Currently, it is considered a low risk
  - New flux-free materials are available for continuous improvement
- Challenge 3: Commercial viability of the whole UTEMPRA system.
  - Commercial viability is intact with a very modest cost increase from base system
  - This modest increase is easily justified by the increase in vehicle range

Any proposed future work is subject to change based on funding levels

Completed & Proposed Future Research

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Specific Annual Objectives – Budget Period 2

- **Budget Period 2 (Nov-15 to Mar-17): System Development Phase**
  - Program management - **Complete**
  - MMFC Prototype Design and Build **– Prototype 1 (Aluminum) – Complete; Prototype 2 (Plastic) – In Progress**
  - Braze Equipment Installation and Qualification **- Complete**
  - Component Builds and Tests (Heat exchangers, Compressor, Valves, Pumps) **– Complete**
  - System Bench Performance Tests **- Complete**
  - Complete CoolSim UTEMPRA system Model and use for Vehicle Controls Development **- Complete**

Specific Annual Objectives – Budget Period 3

- **Budget Period 3 (Apr-17 to Feb-18): Vehicle Build and Demonstration Phase**
  - Program management – Focus on project cost and timing
  - Vehicle Controls – Develop MAHLE controller with control logic and control software.
  - Design Durability Validation of Components – Limited durability testing complemented by analysis & prior component validations.
  - Manufacturing Plan and Cost Estimates – Detailed final cost estimations.
  - Vehicle Build – Follow vehicle packaging study to install components and coolant network
  - Vehicle Testing – Perform (a) thermal testing and optimization at MAHLE Climatic tunnels (b) Range certification at FCA (c) Road testing
  - Final Analysis and Vehicle Delivery to DOE

Any proposed future work is subject to change based on funding levels

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Thank You !

Backup Slide

Vehicle Baseline Testing

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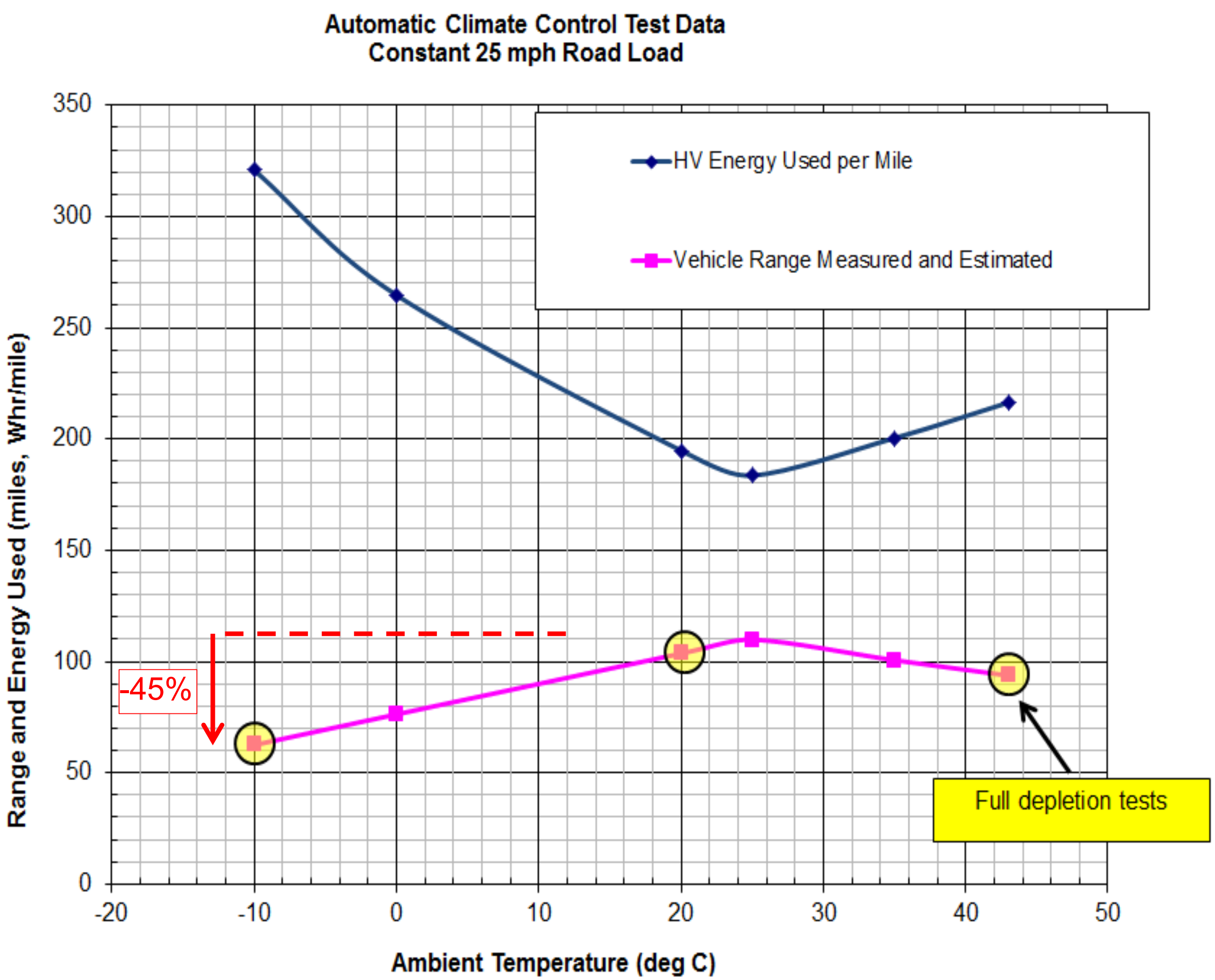

The ACC25 test data was used to estimate the impact of ambient temperature on the vehicle range.

These tests were run at a constant 25 mph condition. Three of the tests were run to near full depletion. The range for the other tests are estimated using the W-hr/mile energy usage.